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In-House Report
March 1990



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PERSONAL COMPUTER (PC) THERMAL ANALYZER

James M. Vaccaro, Douglas J. Holzhauer, Paul S. Yaworsky

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, NY 13441-5700

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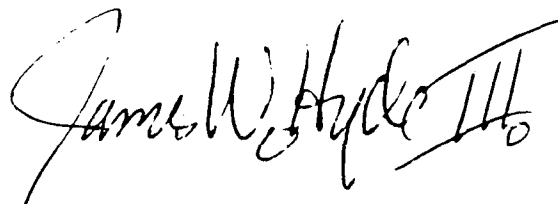
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13. ABSTRACT (Maximum 200 words) Rome Air Development Center (RADC) has developed an expert system based design verification tool to increase the efficiency of calculating device junction temperatures on printed circuit boards (PCBs). This tool, the Personal Computer (PC) Thermal Analyzer, was developed for reliability and electronic design engineers for use during the computer-aided design (CAD) phase. The PC Thermal Analyzer was developed through the combination of two technical areas, thermal analysis and expert systems. This intelligent analyzer is a more effective verification tool because traditional tools require much time and knowledge of thermal analysis, while the PC Thermal Analyzer is quick, requires no expertise in thermal analysis, and provides useful results during the CAD phase. <i>2. This is a... for the... automatic modeling... processes</i>				
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TABLE OF CONTENTS

<u>Chapter</u>	<u>Title</u>	<u>Page</u>
0.0	Executive Summary	1
1.0	Introduction	3
2.0	Thermal Analysis Methods	7
	Finite Difference	9
	Finite Element Analysis	11
	Automatic Modeling Preprocessors	14
3.0	The Solution: Expert Systems	16
4.0	The Personal Computer Thermal Analyzer	20
	A Personal Computer Thermal Analyzer Example	25
	A Finite Difference (FD) Example	33
5.0	Conclusion	36
	Appendix	
	PC Thermal Analyzer Knowledge-Base	37



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LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Failure Rate vs. Temperature	4
2	Thermal Network for Integrated Circuit in Can Package	9
3	Finite Element Model of 14 Pin Dip	11
4	Printed Circuit Board FEA Model	13
5	Expert System Block Diagram	17
6	Consultation Environment	23
7	ECCM Control Processor Board	26
8	Jard Mounted Air-Cooled Coldwall	27
9	Thermal Resistance Network of Printed Circuit Board	33

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
1	Given Information	28
2	Results from Detailed Finite Difference Analysis	31

0.0 EXECUTIVE SUMMARY

Rome Air Development Center (RADC) has developed an expert system based design verification tool to increase the efficiency of calculating device junction temperatures on printed circuit boards (PCBs). This tool, the Personal Computer (PC) Thermal Analyzer, provides reliability and design engineers an alternative to thermal analysis of PCBs. Traditionally, thermal analysis is performed after the computer-aided design (CAD) phase using design tools which require much time and knowledge of thermal analysis. The PC Thermal Analyzer is a more effective tool because it is quick, requires no expertise in thermal analysis and provides useful results during the CAD phase.

The PC Thermal Analyzer was developed by combining two technical areas, thermal analysis and expert systems. Since many reliability and electronic design engineers lack knowledge in both thermal analysis and electronic design, an intelligent tool is needed to improve contemporary thermal analysis. Rule-based expert systems were found to be the most appropriate solution to this deficiency. By incorporating basic thermal design expertise rules into an expert system shell (VP Expert), the PC Thermal Analyzer was constructed.

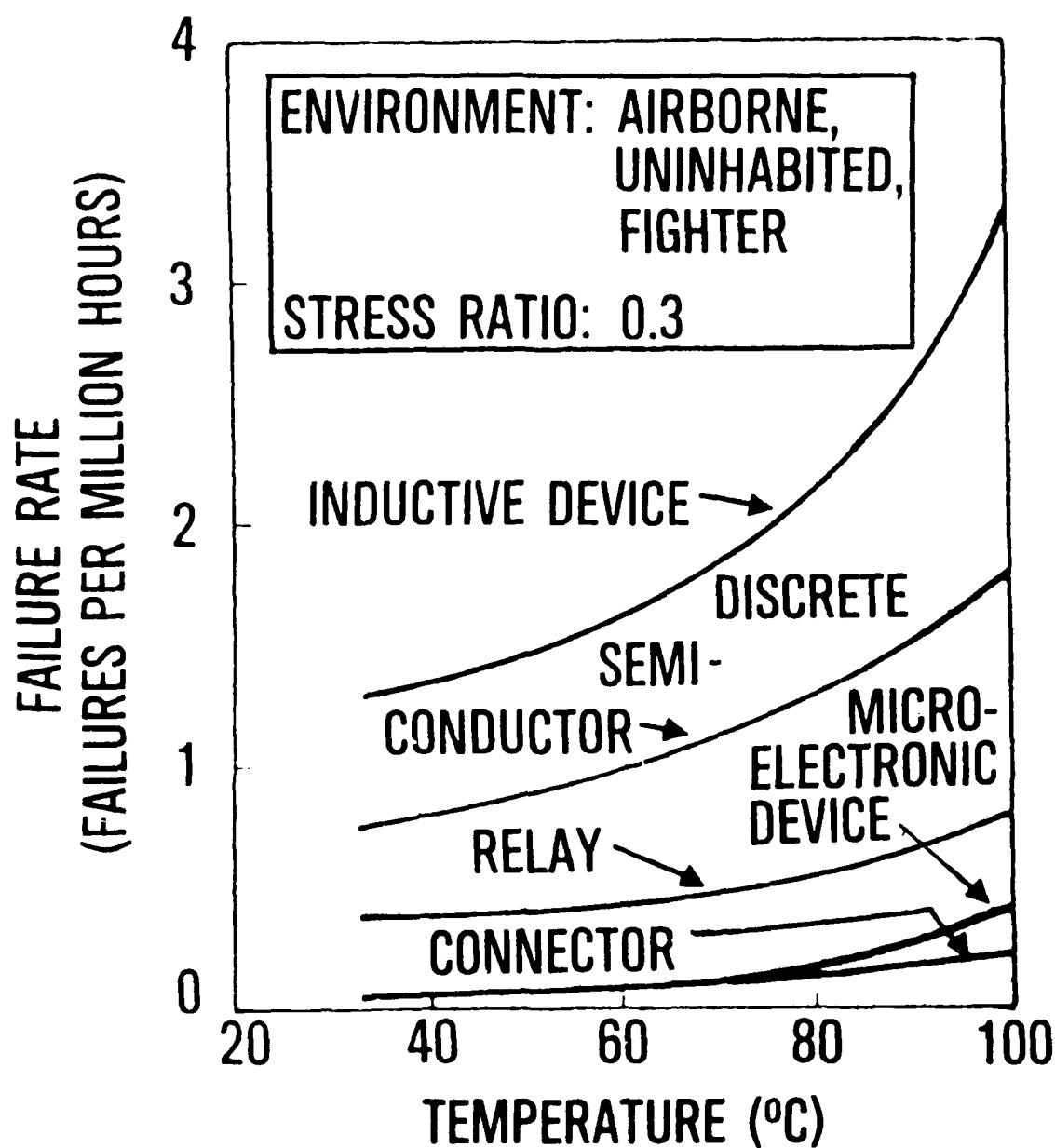
To demonstrate the power of the PC Thermal Analyzer, it was compared with an existing thermal analysis method. Specifically, the PC Thermal Analyzer was measured against a finite difference (FD) thermal analysis method for speed and accuracy. The PC Thermal Analyzer calculated the

maximum device junction temperature in five minutes (including inputting data) with only half of the answers to data input questions known by the user. A thermal design expert, using a computerized FD tool, took eight hours to calculate the maximum junction temperatures for the same PCB. The PC Thermal Analyzer's junction temperature result was only two percent higher than the true maximum. Thus the PC Thermal Analyzer has a place in contemporary thermal analysis since it provides good results quickly and easily.

1.0 INTRODUCTION

The earlier in the design phase that the reliability concerns can be addressed, the more reliable the final product. This is intuitively apparent to reliability engineers. Thermal management is one major reliability concern for electronic systems. The relation between temperature and device reliability has been quantified in the failure rate versus temperature curves in MIL-HDBK-217 (Figure 1). The use of thermal analysis software can help in attaining the reliability requirements and goals. Thermal analysis software tools are currently being used to assess the system's thermal design. Unfortunately, these tools are used after the design is fairly well established. This is because of the excessive amount of input data associated with detailed analysis and because the analysis has to be accomplished by an expert in the field of heat transfer. To make things even worse, this heat transfer expert is typically located in a different group, making communication between the electronics designer and the thermal analyst difficult. The integration of expert system technology with thermal analysis has changed this. It has resulted in the creation of a thermal design evaluation tool that can be an active part of the design process.

Since thermal design has a large impact on the reliability of an electronic system, there have been several Air Force sponsored projects with the goals of increasing the accuracy of system level thermal analysis and in making analysis of printed circuit boards easier and quicker. RADC has sponsored several efforts in the area of thermal design. In 1982 and



Failure Rate vs. Temperature

Figure 1

1984 RADC produced two reports that examined derating of electronic devices. In 1985 an in-house effort produced an algorithm by which the thermal derating can be verified in completed systems. These efforts

culminated in the AFSC Pamphlet Part Derating Guidelines (AFSCP 800-27). In 1988 Wright Research and Development Center (WRDC) produced a computer program that assists in the modeling of a printed circuit board. This computer program works in conjunction with the NISA finite element analysis program to determine the temperature profile. In the area of analysis accuracy the definitive work on thermal resistance of device packages was sponsored by RADC. This effort measured the thermal resistance of 2000 device packages and resulted in Technical Report, Thermal Resistances of JAN Certified Microcircuit Packages, (RADC-TR-86-97). The results of this project were also included in MIL-HDBK-217 and MIL-M-38510. Each of these advances are aimed at affecting the analysis after the design is established.

The results of doing the thermal design assessment during the design phase decreases system costs and increases reliability. This creates a need for a tool that will enable the electronic engineer to quickly assess the thermal management of a proposed design. This can only be accomplished by using nontraditional methods. This project has shown that the integration of expert system technology and empirical thermal analysis algorithms can predict device temperatures with sufficient accuracy while being extremely easy to use.

This report discusses the traditional thermal analysis methods currently used. Their weaknesses are discussed in light of the need for a design-oriented thermal analysis tool. The expert system shell and its method of operation are covered with attention to the specific goal of

thermal analysis. A walk-through of printed circuit board analysis using the PC thermal analyzer is made with a comparison to a traditional finite difference analysis.

2.0 THERMAL ANALYSIS METHODS

Contemporary thermal analysis is accomplished using computer programs that numerically simulate the flow of heat through materials. There are many general purpose analyzers available for use. Since these programs are general purpose, a considerable amount of tailoring is required to adapt them to the particular problem of electronic system thermal analysis. The two major types of thermal analyses used by these programs are finite difference (FD) and finite element analysis (FEA). Although these techniques are different in the method of solution, the information required for each analysis is very similar. Both FD and FEA techniques require detailed information on the:

- 0 geometry of the part being analyzed
- 0 material properties
- 0 location and quantity of heat generated
- 0 type and quantity of cooling available*

*The two primary methods for cooling PCBs are convection and conduction. Conduction cools a board through the transfer of heat from the chips on the board to a heat sink plate on the other side of the board. Convection cools a board by transferring heat off the surface of the thermal plate to a moving mass of fluid (air). As the air heats, the density of the air is lessened, causing the heat to rise out of the case. Often, a fan forces the air out of the case quickly making convection a reasonable form of cooling PCBs. Conduction occurs through the solid materials (heat sink plate, chips, interconnects and board) and through air (for air space less than 1/4 inch between the heat sink plate and the board). Although air has a high heat flow resistance, conduction is usually the best method for cooling PCBs.

This information is then used to model the actual problem by reducing it to a mathematical relationship. With these algorithms, the general purpose computer programs provide a much improved way of modeling physical systems. This is especially true with the use of a graphical preprocessor (i.e. automatic modeling software). These general purpose analyzers (FD and FEA programs) are independent of the system's function and are only concerned with the heat flow through the system.

The use of traditional computer codes (FD and FEA) for thermal analysis requires the engineer to possess specific knowledge in the:

- 0 area of thermal analysis
- 0 workings of the analysis code and its graphics preprocessor
- 0 material properties
- 0 reduction of the loading conditions to their mathematical equivalent

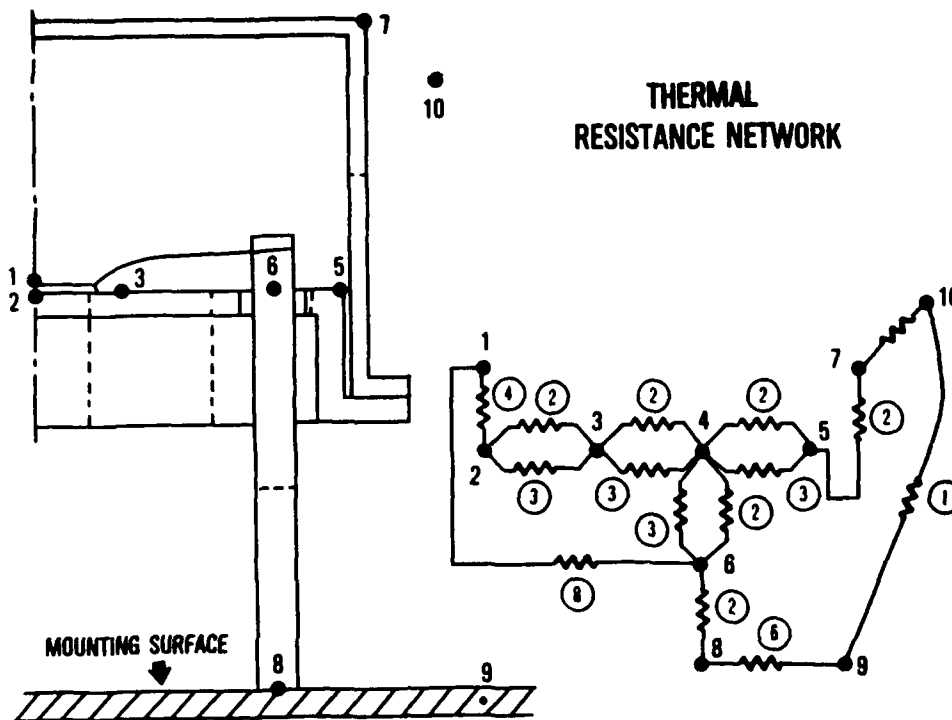
The complex geometry of a printed circuit board (PCB), along with its many different materials, presents a technical challenge to the mechanical engineer in reducing it to an equivalent mathematical model. In spite of this complexity, the thermal analysis of avionics or advanced ground systems is a necessary part of the reliability assessment because of the serious effects temperature has on system and component reliability.

Finite Difference

Finite difference software programs provide the user with a tool which can be used for electronic device or system thermal analysis using a "network model" of the device or system (e.g. PCB). The network model is developed through Kirchhoff's laws:

- 0 the sum of the heat entering a junction is equal to the sum of the heat leaving the junction
- 0 around any closed loop, the sum of the temperature increases equals the sum of the temperature decreases

An example of a thermal resistance network model is shown in Figure 2. The



Thermal Network for Integrated Circuit in Can Package

Figure 2

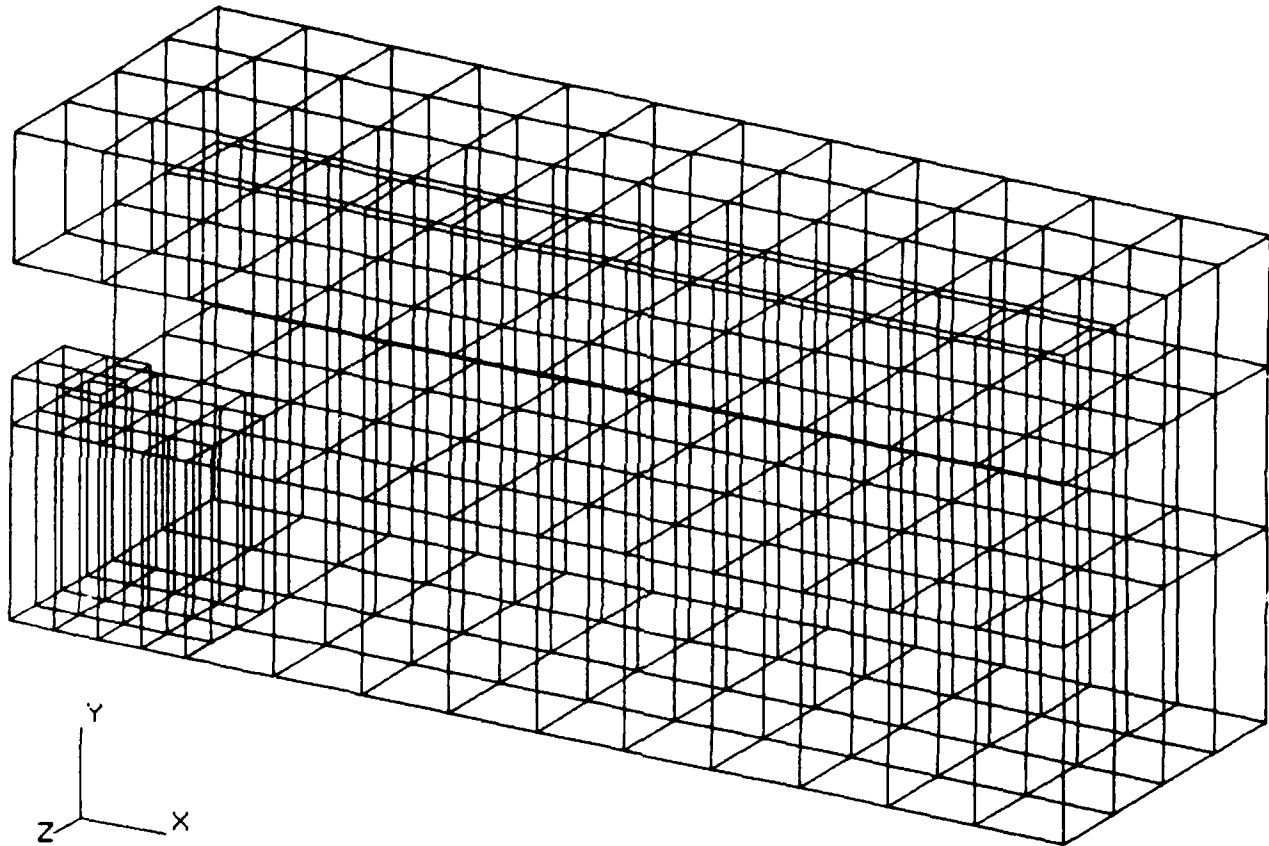
engineer creates an analog circuit that is a resistor network equivalent to the thermal resistances associated with the specific PCB design. After the engineer forms this analytical model, the data must be carefully formatted and input into a file. The data and format needed depend on the program being used. One of the most popular finite difference programs is the "System Improved Numerical Differencing Analyzer" (SINDA) Program, which was developed by TRW Systems Group for the National Aeronautics and Space Administration (NASA). For the SINDA Program, the input data includes the:

- 0 heat sources
- 0 conductors
- 0 nodes (i.e. 4 nodal attributes)
 - number
 - temperature
 - location
 - type

The amount of data for a device is usually small (e.g. a dozen nodes, a source and a conductor), but the amount of data for a PCB is usually immense (e.g. hundreds of nodes and dozens of sources and conductors). One to a dozen data elements are easy to implement, but inputting hundreds of elements can be extremely time consuming. Another finite difference program is the "Thermal Analysis Program" (TAP). TAP can handle 750 nodes, 1800 resistors, 1800 capacitors and 3400 tabular inputs. These numbers are not inviting if the user needs a quick result, because it takes an enormous amount of time to input large amounts of data completely and correctly.

Finite Element Analysis

Finite element analysis (FEA) software programs also provide the user with a tool which calculates device junction temperatures. To input "finite elements" (e.g. three dimensional cubes) of the design into the FEA program, it is important to construct a "geometric model" (Figure 3).



(1/4 of package)

Finite Element Model of 14 Pin Dip

Figure 3

Forming the correct model is difficult. It takes time and experience in geometric modeling and thermal analysis to create an accurate model. Even if the engineer has the time, inexperienced engineers lack the knowledge and can sometimes produce incorrect geometric models without expert advice.

"Numerically Integrated Elements for Systems Analysis" (NISA) is an example of a FEA software program. The FEA program NISA, developed by Engineering Mechanics Research Corporation (EMRC), has the capability of performing thermal analysis. To use NISA effectively, it is necessary to develop a finite element model of the particular electronic system. If all the characteristics of the PCB are known, it is possible to develop a good model of the PCB in a few hours. These characteristics include:

- 0 heat outputs
- 0 geometric data
- 0 material thermal conductivity

If the user does not know one of the above parameters, the analysis accuracy will suffer. For example, a simple finite element model for devices on a PCB is shown in Figure 4. Without the necessary information, the finite element program loses its accuracy. With FEA, the user models the PCB as a collection of solid shapes (such as Figure 4). After the modeling and analysis, FEA can give very detailed information on the temperature distribution of the board. However, for reliability predictions, this degree of accuracy is not needed.


E.M.R.C.- DISPLAY II POST-PROCESSOR VERSION 89.0

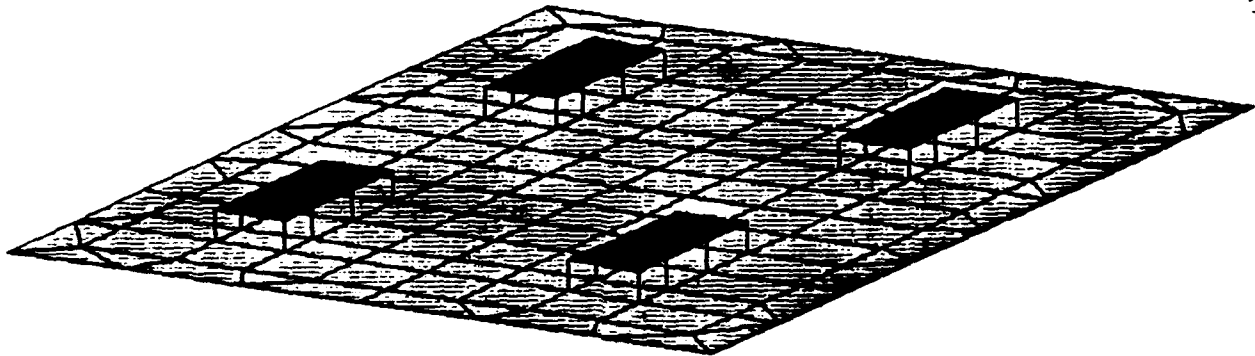
ISOTHERM CONTOURS

STEADY-STATE HEAT

VIEW : -4.00E+01

RANGE : -3.07E+01

 RX= -75
RY= 0
RZ= 60



Printed Circuit Board FEA Model

Figure 4

Automatic Modeling Preprocessors

To make modeling easier and faster for FD or FEA (e.g. NISA programs), automatic modeling software was developed to generate models for PCB thermal analysis. These preprocessor programs are used in conjunction with both FD and FEA thermal analysis programs. In other words, modeling programs provide a data preprocessor for PCB thermal analysis software. For example, the automatic modeling program THERMAL* creates a NISA input file for stress and thermal analysis. To use this program effectively, the PCB must be fully characterized. The following must be known:

- 0 board dimensions
- 0 material properties of the board
- 0 attributes of electronic devices
 - position
 - type
 - heat output

Since these automatic modelers also require an abundance of specified information, they are not a viable solution for a quick system thermal analysis. Additionally, today's modelers have far too many weaknesses:

- 0 models are often too large and, therefore, drain computer resources (time and memory)
- 0 information requested by the program may not be known by the user

* Created by Engineering Mechanics Research Corporation (EMRC) for Lockheed Aeronautical Systems Company, Burbank CA under contract from the Air Force Wright Aeronautical Lab (AFWAL).

- 0 only limited cooling system options are available
- 0 modelers require an extensive amount of input data

Summary

The finite difference, finite element and automatic modeling programs are useful in their own right, but there are certain deficiencies they all possess. The software programs all require:

- 0 large amount of input data
- 0 input data to be accurate and in the correct format (models, etc.)
- 0 users to have basic knowledge in thermal analysis

For many applications there is a better approach. The following sections will show how the integration of thermal analysis and expert systems technology can create a tool that addresses the need for thermal analysis verification early in the design phase of a system.

3.0 THE SOLUTION: EXPERT SYSTEMS

A variety of approaches exist which might seem to alleviate the problems of the current deterministic thermal analysis programs. These thermal analysis codes are labeled deterministic because "everything has to be known" in order for the programs to run properly. The approaches taken have yielded "elaborate automatic modelers" that only disguise the problems. At most, these automatic modelers put a better interface on the existing finite difference and finite element programs. Consequently, all the deficiencies discussed earlier are still not solved. The use of an expert system to handle thermal analysis is one approach which solves these deficiencies. An expert system thermal analyzer will not replace the current thermal analysis programs. Instead, this expert system will be an application which predicts junction temperatures of PCB devices with estimated results in a fraction of the time. The expert system thermal analyzer approach overcomes the deficiencies associated with traditional thermal analysis programs. The Personal Computer (PC) Thermal Analyzer requires very few inputs and limited knowledge of thermal analysis and electronics.

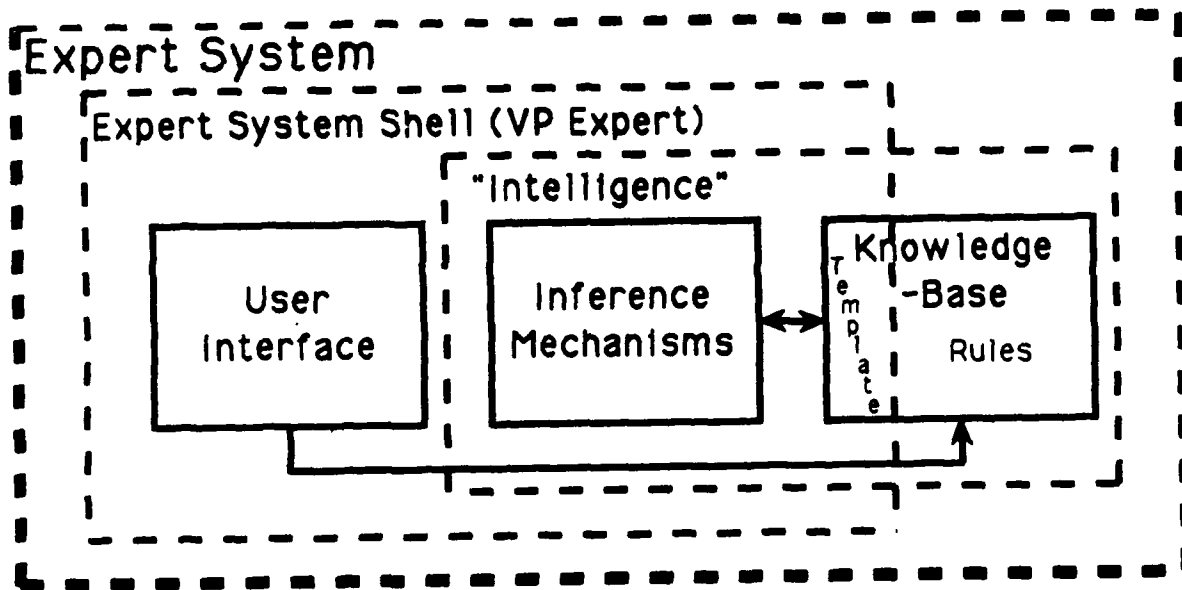
To appreciate this concept, it is important to briefly review background in artificial intelligence and expert systems. "Artificial Intelligence" is a broad concept encompassing a number of different fields and applications. Included in "AI" is expert system technology, which utilizes computer software to emulate the way people solve problems. Like a human expert, an expert system gives advice by drawing upon its own store

of knowledge and requesting information specific to the problem at hand.

An expert system is composed of:

- 0 a user interface
- 0 the mechanisms necessary to infer the knowledge
- 0 a knowledge-base which stores all the expert information

These three parts are illustrated in Figure 5 below. The "knowledge" is



Expert System Block Diagram

Figure 5

stored in rules (IF-THEN statements) encoded in the knowledge-base; specific information is provided by the user seeking expert advice. The "intelligence" of an expert system is the interaction between the inferring mechanisms and the knowledge-base. This "intelligence", along with

the user input (interface), allows the software to make expert decisions. The decisions are good if the knowledge-base (expert information) is detailed and accurate, and the inferring mechanisms are appropriate. In other words, with good information and the proper tools to use it, an expert system can be built to solve a specific task. The PC Thermal Analyzer was developed this way. This prototype is a pre-existing tool (expert system shell, Figure 5) and a knowledge-base with expert knowledge on junction temperatures of PCBs.

Expert system programs can now be compared to the thermal analysis programs discussed earlier. First of all, "knowledge" can be broken down into two categories: "public" and "private". Here, "Public knowledge" refers to the socially accepted truths of today, such as mathematics, physics and other algorithmic formulas. "Private knowledge" refers to the learning associated with one's experiences, such as rules of thumb and/or heuristics. Traditional thermal analysis programs stress public knowledge. Expert systems combine both public and private knowledge, emphasizing the latter. Expert systems provide the means for combining both accepted truths and rules of thumb in a knowledge-base through the use of a template. This template, for our purposes, is rule-based (discussed in more detail later). Expert systems emphasize private knowledge and therefore are useful in solving problems based on human insight and heuristics, while the thermal analysis programs rely strictly on brute force computation of accepted truths (Kirchhoff's laws, etc.)

In summary, an expert system can alleviate many of the problems stated earlier concerning thermal analysis programs. Thermal analysis programs require a large amount of precise data and some technical expertise in the area of thermal analysis. An expert system thermal analyzer requires very few inputs and no knowledge of thermal analysis.

4.0 THE PERSONAL COMPUTER THERMAL ANALYZER

The Personal Computer (PC) Thermal Analyzer Prototype (expert system) is a "proof of concept" for the development of a complete PC thermal analyzer system. This PC thermal analyzer system will give the reliability/system engineer, who may have limited knowledge in thermal analysis, the maximum junction temperatures for a particular board. The complete system will contain expertise encompassing all types of thermal analysis methods with associated "rules of thumb". Also, the analyzer system will contain all the state-of-the-art cooling techniques for PCBs.

The PC Thermal Analyzer Prototype provides a feasibility demonstration for this technology. The prototype possesses the capability to analyze any particular PCB that uses air-cooled coldwall type of cooling. The expertise in the area of thermal analysis was supplied by a mechanical engineer in the reliability field and by the RADC Thermal Reliability Handbook. The rules from this expertise were incorporated into an expert system shell and are stored on a single 5 1/4" floppy disk. We will discuss the details of the expert system shell and the knowledge-base (rules of expertise), followed by an example of the analyzer in action.

VP Expert is an expert system software shell, produced by Brian Sawyer and published by Paperback Software International, which contains (see Figure 5):

0 a user interface

- 0 the inference mechanisms
- 0 a template in the knowledge-base

The user interface is a collection of windows (screens) with selectable commands. To load VP Expert, the user inserts the disk and types "VPX" at the "DOS" prompt (A). A window appears with a variety of commands. These commands are located at the bottom of the screen and can be chosen by the arrow keys and selected by pressing "return". Two important commands are "edit", which allows the user to edit a particular knowledge-base, and "consult" which allows the user to consult any knowledge-base. The knowledge-base (Appendix) includes a:

- 0 template
- 0 actions block
- 0 rules block
- 0 questions block

The template is the interface between the rules and the inference mechanisms (see Figure 5). The template is, in simple terms, the syntax associated with the knowledge-base. For example, rules must be in the proper format

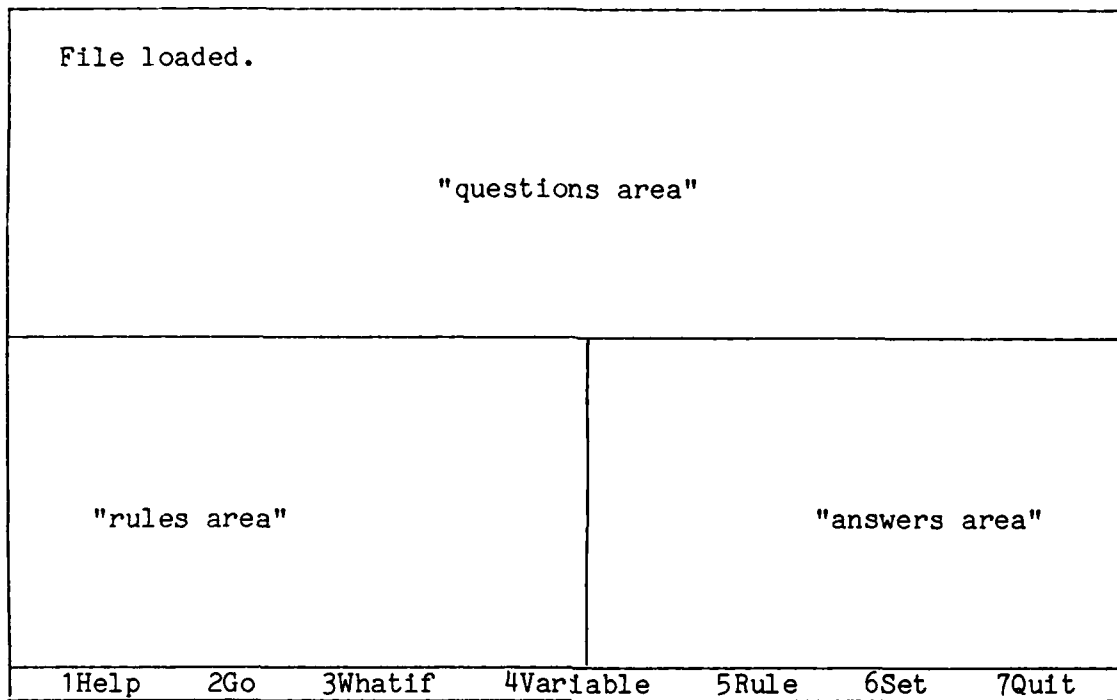
```
(RULE rule_label
  IF condition1 (AND/OR)
    condition2 (AND/OR)
    (etc.)
  THEN conclusion1
    conclusion2
    (etc.)
  ELSE conclusion3
    conclusion4
    (etc.);)
```

or the knowledge put into the template is not accepted by the inference mechanisms. The actions block appears first in the knowledge-base and is composed of "display information" and "find clauses". The find clause

(Find <"variable">)

finds the value of the associated variable. The actions block will automatically print the display information on the screen and find the variables, all in the order presented. The rules block is composed of all the "rules of thumb" and facts. The questions block, which appears last, gives the questions necessary to acquire information from the user. The knowledge-base works in cooperation with the expert system shell through the template and inference mechanisms to compose an intelligent system.

After loading VP Expert, the "edit" or "consult" command may be selected. Editing the particular PC Thermal Analyzer knowledge-base requires the user to select the edit command and then select the file "PC_Therm". All commands are chosen by the arrow keys (or mouse) and selected by pressing "return" unless otherwise specified. Once in the knowledge-base, rules may be added or deleted at the user's discretion. After the editing is complete, the user saves the changes and exits the knowledge-base by selecting "save" and "quit", respectively. Once exited, the user may select the "consult" command. A consultation, in expert system terms, is the environment (Figure 6) in which the expert system is



Consultation Environment

Figure 6

run. This environment is the composition of three areas:

- 0 a "questions area" located in the upper half
- 0 a "rules area" located in the lower-left quadrant
- 0 an "answers area" located in the lower-right quadrant

The question area is where the user feeds in his information. The user answers the questions given as they appear on the upper screen. The user types in a reply or selects the appropriate choice depending on the type of question. If the question requires a choice

(e.g. "What is the Board's Function?"
MEMORY COMPUTER),

the user selects the best one. If the question is fill-in-the-blank

(e.g. "What is the Air Flow Rate in kg/min?"
_____),

then the user types in the correct response or types a "?" if unknown. The expert system has a way of finding the unknown answers through the inference mechanisms. The mechanisms either default to a standard answer, or ask the user for more information through additional questions. The rules area illustrates the find commands being implemented and the rules being used by the inference mechanism. The answer area illustrates all the variable values associated with each find command as they are implemented. The user may watch the screens in slow motion during a consultation by selecting the "Set" command at the bottom of the screen and then by selecting the "Slow" command several times before starting the consultation. The more the "Slow" command is selected, the slower the consultation. To start a consultation, the "Go" command should be selected.

A Personal Computer (PC) Thermal Analyzer Example

Here is an example of the PC Thermal Analyzer in action. This example includes an Electronic Counter Counter Measure (ECCM) Control Processor Board Assembly (Figure 7) that has an attached heat sink plate. The cooling of the integrated circuits (ICs) is accomplished by the heat flowing through the attached heat sink plate (metal) to the air cooled coldwalls (Figure 8) which are the final heat sink. Design information supplied by a contractor at CDR is given in Table 1. The PC Thermal Analyzer can use this design information to reach a good approximation of the maximum junction temperature for the board within a few minutes.

In this example, the first area to describe is the questions area (Figure 6). After selecting "Go" in the consultation environment, the questions area will present this:

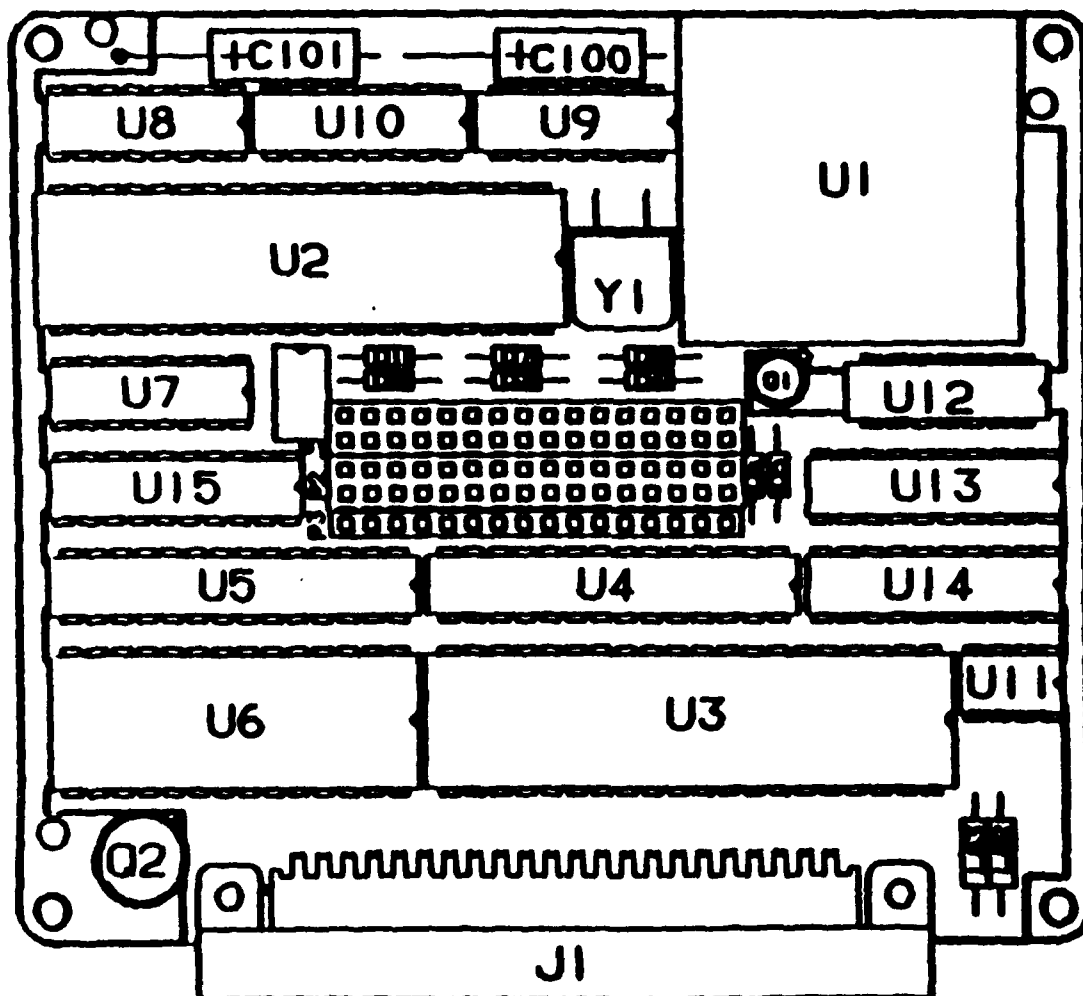
"Welcome to the PC Thermal Analyzer. This Prototype demonstration will calculate the maximum Junction Temperature for printed circuit boards with Card-Mounted, Air-cooled coldwalls.

Press any key to begin consultation."

After pressing a key, the analyzer starts to ask the user some questions:

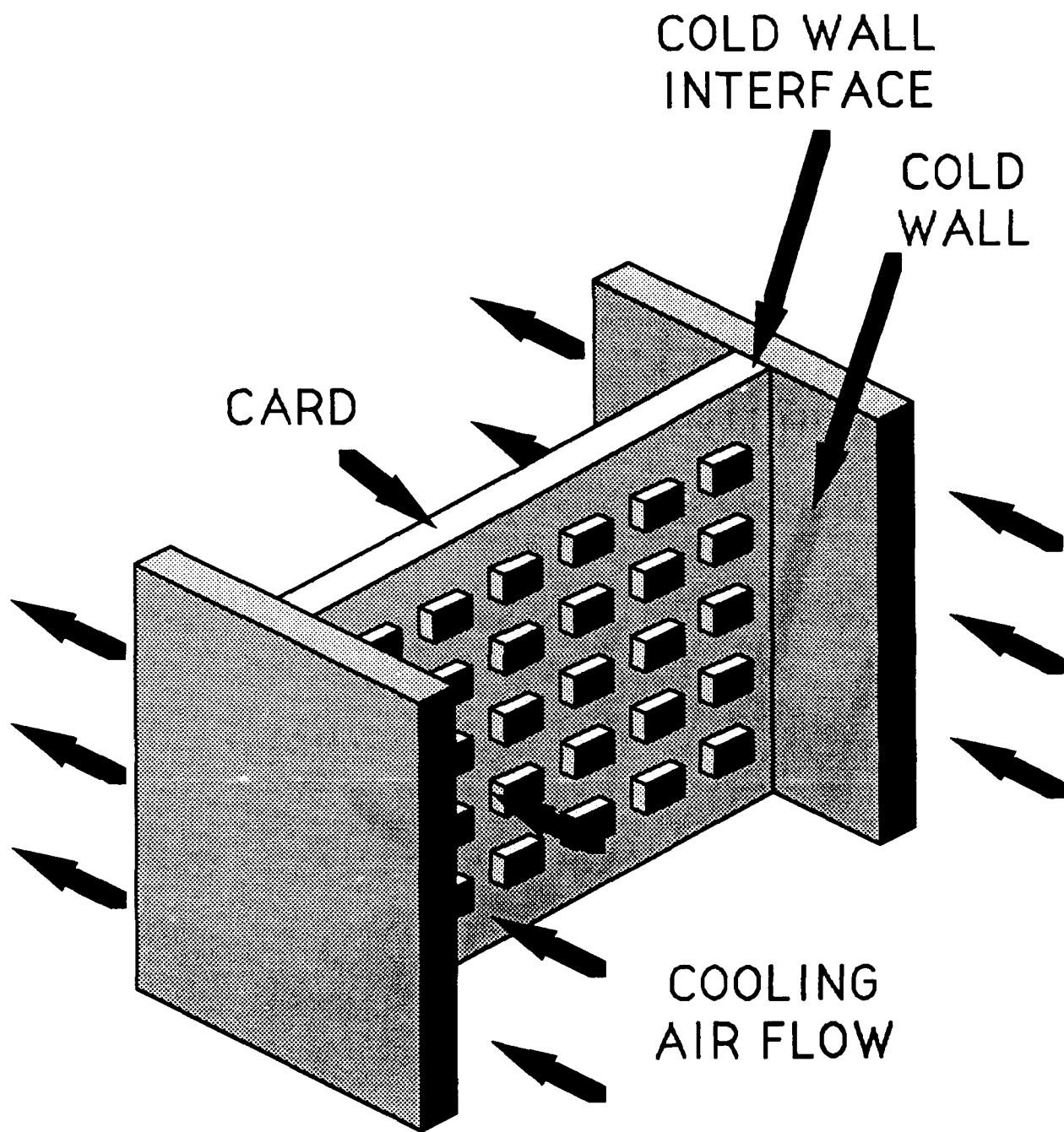
- ((1) What is the Ambient (air inlet) Temperature in degrees centigrade?
- (2) What is the total Heat Output (power dissipation) in watts?).

BOARD ASSEMBLY



ECCM Control Processor Board

Figure 7



Card Mounted Air-Cooled Coldwall

Figure 8

COMPONENT	POWER DISSIPATED (Watts)		
Q1	.21		
U1	.15		
U2	.275		
U3	.275		
U4	.33		
U5	.33		
U6	.33		
U7	.33		
U8	.33		
U9	.056		
U10	.036		
U11	.001		
U12	.001		
U13	.06		
U14	.33		
U15	.33		
Total	3.374		
<table> <tr> <td><u>Air Inlet Temperature</u> 71°C</td><td><u>Mass Flow Rate</u> .48 kg/min</td></tr> </table>		<u>Air Inlet Temperature</u> 71°C	<u>Mass Flow Rate</u> .48 kg/min
<u>Air Inlet Temperature</u> 71°C	<u>Mass Flow Rate</u> .48 kg/min		
<u>Heat Sink Plate Material</u> Aluminum			

Given Information

Table 1

The answers to questions (1) and (2) are taken from the information given, 71 and 3.374, respectively. Unfortunately, all the questions asked are not this straightforward, such as:

((3) What is the Temperature difference between the center of the card and the card edge in degrees centigrade?)

This question requires information not available. The user only needs to type "?" and press return to signify to the PC Thermal Analyzer that this information is unknown. To find the best approximate solution, the analyzer will ask for other information relevant to the previous question:

((4) What is the material of the Thermal Plane?).
ALUMINUM COPPER

The material of the plane is given to be aluminum. After selecting aluminum, other questions are asked:

((5) What is the thickness of the thermal plane?

((6) What is the width of the card in meters?

((7) What is the height of the card in meters?).

Since the information is unknown, "?" is the answer to all these questions.

In this case, another relevant question is asked:

((8) How many Devices (ICs or transistors)?).

This question is answered by counting the devices (16) on the board. After 16 is input, four additional questions are asked:

- ((9) What is the Junction-to-Case Thermal Resistance in C/Watt?
- ((10) What is the Package Type for the device with the highest heat output?
DIP FLATPACK CHIP_CARRIER
- ((11) What is the Case-to-Mounting Surface Thermal Resistance in C/Watt?
- ((12) How many Pins are on the device with the highest heat output?).

All of these questions have unknown answers. The tenth question requires a selection, so "DIP" is selected. The other questions receive a "?" from the user. The final two questions are:

- ((13) What is the Heat Output (Watts) for the device with the highest output?
- ((14) What is the Air Flow Rate in kg/min?).

They may be answered .33 and .48, respectively, from the information given. Finally, the PC Thermal Analyzer reveals the answer:

"The maximum Junction Temperature is computed to be 99.4 C."

The true junction temperatures are given in Table 2. Comparison of the analyzer's answer to that of the highest junction on the board reveals a small difference ($99.4 - 97.5 = 1.9$). The percentage error ($((1.9/97.5) * 100)$) is very small (2%).

To better understand how these questions were asked and how their answers were incorporated into a solution, the rules and answers areas will be described for this example. In this description, all find clauses and

COMPONENT	JUNCTION TEMPERATURES (°C)
Q1	96.0
U1	88.0
U2	96.1
U3	93.8
U4	97.5
U5	96.4
U6	95.1
U7	95.7
U8	95.7
U9	86.9
U10	86.3
U11	88.5
U12	88.5
U13	97.5
U14	97.5
U15	97.5

Results from Detailed Finite Difference Analysis

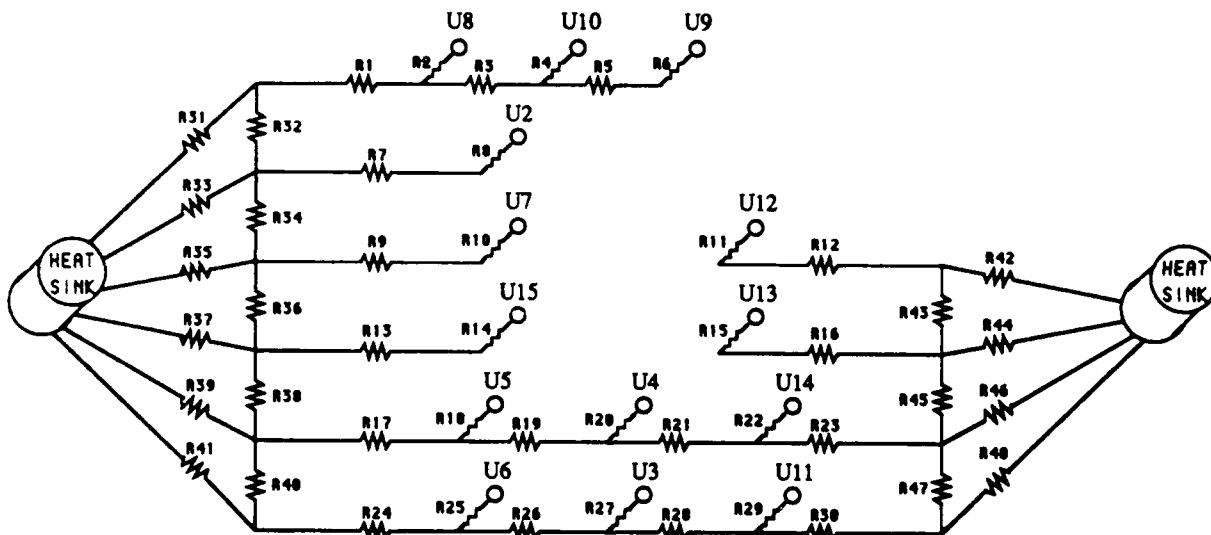
Table 2

rules will be in the rules area and all the answer statements will be in the answers area (Figure 6). This description will follow directly from the questions area explanation. The Appendix (knowledge-base) is a helpful reference. After selecting "Go" to start the consultation and pressing any key, the rules area indicates (Find TA1) that the consultation is looking for the ambient temperature. This is why question (1) is asked. After question (1) is answered, rule 1 (Appendix) is induced and passes,

setting the ambient temperature ($TA = TA1$) to the answer (71). Rule 1 appears in the rules area and the answer ($TA = 71$) appears in the answers area. Next, another find (Find QT1) is implemented to display question (2). A similar scenario is accomplished for question (2) with rule 2. Question (3) receives a "?" answer which indicates it is unknown. This induces rule 4 and it fails, then rule 5 is induced and it passes. Rule 5 in turn orders the consultation to find the material (Find MAT; question (4)) and the thickness (Find TH; question (5)). Since the answer to question 4 is known, it behaves the same as questions (1) and (2), using rule 46. Question five's answer ("0.04") induces rules 6, 7, 8 and 9 before it reaches an answer (0.04). Questions (6) and (7) react similarly, inducing rules 21 and 22, and rules 44 and 23, respectively. The answer (16) to question (8) induces rule 40, which sets the number of devices ($NOD = 16$) to sixteen. The answer "?" to questions (9-12) induces the rules 24, 25, 28, 29, and 45, respectively. The final two questions (13) and (14) induce the rules 35, 46, and 47. Rule 47 gives the solution ($TJ = 99.4$).

A Finite Difference (FD) Example

For comparative purposes, the finite difference thermal analysis for the same Electronic Counter Counter Measure Control Processor printed circuit board is reviewed here. The main part of doing a finite difference analysis is the production of a thermal resistance network. The network for this printed circuit board is shown in Figure 9. The network consists



Thermal Resistance Network of Printed Circuit Board

Figure 9

of nodes that are connected by thermal resistances. The nodes are points of interest, where the temperatures are known (or need to be predicted), where heat is being produced or where there is a change in geometry or material properties. The thermal resistors are determined by the geometry

and the material properties, and indicate resistance to heat flow between the nodes. Conduction thermal resistance is obtained by hand calculation using the formula:

$$R = (K * A) / D$$

Where R = Thermal resistance

 K = Material conductivity

 A = Cross sectional area between the nodes

 D = Linear distance between the nodes

There are over 50 thermal resistors and over 25 nodes in this network. Both the nodes and the thermal resistance values are input data for the finite difference analysis. In addition, a listing of which nodes the various resistors are attached, the heat output of the nodes that simulate the integrated circuits, and the temperature of the heat sink node must be included in the input file. After inputting this data and running the finite difference program, the results of this analysis will be the list of integrated circuit junction temperatures that was shown in Table 2. Once the details of the design are known, this type of analysis will result in a very accurate prediction of the device junction temperatures.

Summary

Unfortunately, the above FD Example took hours to complete by an experienced mechanical engineer. An engineer unfamiliar with the details of thermal analysis would take days to complete this example correctly,

while this same engineer could use the PC Thermal Analyzer and complete this task within five minutes with only a minor loss in accuracy (2%).

The PC Thermal Analyzer Example described above is not as complicated as it might seem. All the user has to do is run the consultation and answer the questions. The example consultation takes less than five minutes to implement and all the rule checking and answer finding is done automatically. The user knew only 6 out of 14 questions, but despite this lack of information, the analyzer produced a good approximation (2% error). Based on the amount of effort and information necessary to predict the maximum junction temperature, this analyzer provides a very feasible approach to PCB thermal analysis.

5.0 CONCLUSION

The PC Thermal Analyzer is a tool which predicts the maximum device junction temperature of a PCB quickly, for a reliability or electronic design engineer. The maximum junction temperatures are an important factor in determining the reliability in an electronic system. The addition of this tool in the design process will provide a quick and effective way to improve reliability. Contemporary programs are valuable in detailed thermal analysis, but there are times in the design process where quick thermal analysis results are necessary. For example, during a Preliminary or Critical Design Review (PDR or CDR), a design can be checked by running the PC Thermal Analyzer and taking these results and comparing them to the requirements. If the results are unsatisfactory, the problems can be addressed before the product is manufactured. To ensure R&M in the design, the analyzer can be used during the design phase by anyone involved in the design.

This paper has shown that a prototype PC-based expert system is a very feasible approach to PCB thermal analysis. Based on the deficiencies of contemporary thermal analysis methods and the advantages of expert system technology, an expert system thermal analyzer can be an effective tool for improving electronic systems Reliability and Maintainability (R&M). Consequently, a complete analyzer system should be developed based on this "proof of concept".

APPENDIX

PC Thermal Analyzer Knowledge-Base

ACTIONS

```
DISPLAY "
DISPLAY "Welcome to the PC Thermal Analyzer. This Prototype
DISPLAY "demonstration will calculate the maximum Junction
DISPLAY "Temperature for printed circuit boards with Card-Mounted,
DISPLAY "Air-cooled coldwalls.
DISPLAY "
DISPLAY "Press any key to begin consultation.
DISPLAY "
```

```
    FIND TA1
    FIND TA
    FIND QT1
    FIND QT
    FIND TCE1
    FIND TCE
    FIND WD1
    FIND WD
    FIND TJC1
    FIND TJC
    FIND TCB1
    FIND TCB
    FIND QP1
    FIND QP
    FIND MA1
    FIND MA
    FIND TJ
```

```
DISPLAY "
DISPLAY "The maximum Junction Temperature is computed to be (TJ) C.";
```

```
RULE 1
IF TA1 = UNKNOWN
THEN TA = 55
ELSE TA = (TA1 * 1);
```

```
RULE 2
IF QT1 <> UNKNOWN
THEN QT = (QT1 * 1);
```

```
RULE 3
IF NOD <> UNKNOWN AND
   QP <> UNKNOWN
THEN QT = ((NOD * QP) * 1);
```

```

RULE 4
IF TCE1 <> UNKNOWN
THEN TCE = (TCE1 * 1);

RULE 5
IF MAT = ALUMINUM AND
  TH < 0.000254
THEN TCE = ((160 / 7) * QT);

RULE 6
IF MAT = ALUMINUM AND
  TH >= 0.000254 AND
  TH < 0.000508
THEN TCE = (12 * QT);

RULE 7
IF MAT = ALUMINUM AND
  TH >= 0.000508 AND
  TH < 0.000762
THEN TCE = (5.7 * QT);

RULE 8
IF MAT = ALUMINUM AND
  TH >= 0.000762 AND
  TH < 0.00102
THEN TCE = ((120 / 31) * QT);

RULE 9
IF MAT = ALUMINUM AND
  TH >= 0.00102 AND
  TH < 0.00127
THEN TCE = ((60 / 21) * QT);

RULE 10
IF MAT = ALUMINUM AND
  TH >= 0.00127 AND
  TH < 0.001904
THEN TCE = ((16 / 7) * QT);

RULE 11
IF MAT = ALUMINUM AND
  TH >= 0.001904 AND
  TH < 0.00254
THEN TCE = ((13 / 8) * QT);

RULE 12
IF MAT = ALUMINUM AND
  TH > 0.00254
THEN TCE = ((20 / 17) * QT);

```

```

RULE 13
IF  MAT = COPPER AND
   TH < 0.000254
THEN TCE = ((80 / 7) * QT);

RULE 14
IF  MAT = COPPER AND
   TH >= 0.000254 AND
   TH < 0.000508
THEN TCE = (6 * QT);

RULE 15
IF  MAT = COPPER AND
   TH >= 0.000508 AND
   TH < 0.000762
THEN TCE = (2.85 * QT);

RULE 16
IF  MAT = COPPER AND
   TH >= 0.000762 AND
   TH < 0.00102
THEN TCE = ((60 / 31) * QT);

RULE 17
IF  MAT = COPPER AND
   TH >= 0.00102 AND
   TH < 0.00127
THEN TCE = ((30 / 21) * QT);

RULE 18
IF  MAT = COPPER AND
   TH >= 0.00127 AND
   TH < 0.001904
THEN TCE = ((8 / 7) * QT);

RULE 19
IF  MAT = COPPER AND
   TH >= 0.001904 AND
   TH < 0.00254
THEN TCE = ((6.5 / 8) * QT);

RULE 20
IF  MAT = COPPER AND
   TH > 0.00254
THEN TCE = ((10 / 17) * QT);

RULE 21
IF  WDI <> UNKNOWN
THEN WD = (WD1 * 1);

```

```

RULE 22
IF HT <> UNKNOWN AND
  WD = UNKNOWN
THEN WD = (HT / 2);

RULE 23
IF HT = UNKNOWN AND
  WD = UNKNOWN AND
  NOD <> UNKNOWN
THEN WD = (NOD * 0.005);

RULE 24
IF TJC1 <> UNKNOWN
THEN TJC = (TJC1 * 1);

RULE 25
IF PT = DIP
THEN TJC = 24;

RULE 26
IF PT = FLATPACK
THEN TJC = 22;

RULE 27
IF PT = CHIP_CARRIER
THEN TJC = 18;

RULE 28
IF TCB1 <> UNKNOWN
THEN TCB = (TCB1 * 1);

RULE 29
IF PT = DIP AND
  NOP <= 20
THEN TCB = 20;

RULE 30
IF PT = DIP AND
  NOP > 20
THEN TCB = 15;

RULE 31
IF PT = FLATPACK AND
  NOP <= 20
THEN TCB = 15;

RULE 32
IF PT = FLATPACK AND
  NOP > 20
THEN TCB = 10;

```

```

RULE 33
IF PT = CHIP_CARRIER AND
  NOP <= 24
THEN TCB = 10;

RULE 34
IF PT = CHIP_CARRIER AND
  NOP > 24
THEN TCB = 5;

RULE 35
IF QP1<> UNKNOWN
THEN QP = (QP1 * .1);

RULE 36
IF TEC = BIPOLAR
THEN QP = 0.3;

RULE 37
IF TEC = CMOS OR
  FUNC = MEMORY
THEN QP = 0.1;

RULE 38
IF TEC = DONT KNOW AND
  FUNC = COMPUTER
THEN QP = 0.2;

RULE 39
IF MA1 = UNKNOWN
THEN MA = 1.8
ELSE MA = (MA1 * 1);

RULE 40
IF NOD1<> UNKNOWN
THEN NOD = (NOD1 * 1);

RULE 41
IF PT = DIP
THEN NOD = ((HT * WD) / 2);

RULE 42
IF PT = FLATPACK
THEN NOD = ((HT * WD) * 1);

RULE 43
IF PT = CHIP_CARRIER
THEN NOD = ((HT * WD) / 0.5);

```

```

RULE 44
IF HT = UNKNOWN AND
  WD <> UNKNOWN
THEN HT = (WD * 2);

RULE 45
IF NOP1 = UNKNOWN
THEN NOP = 10
ELSE NOP = (NOP1 * 1);

RULE 46
IF TH1 = UNKNOWN
THEN TH = 0.00102
ELSE TH = (TH1 * 1);

RULE 47
IF TA <> UNKNOWN AND
  QT <> UNKNOWN AND
  MA <> UNKNOWN AND
  TCE <> UNKNOWN AND
  WD <> UNKNOWN AND
  QP <> UNKNOWN AND
  TJC <> UNKNOWN AND
  TCB <> UNKNOWN
THEN TJ = (TA + ((0.03 * QT) / MA) + TCE + (QT * ((0.0761 / WD) + 0.25)) +
  (QP * (TJC + TCB)));

ASK TA1: "What is the Ambient (air inlet) Temperature in degrees centi-
grade?";

ASK QT1: "What is the total Heat Output (power dissipation) in Watts?";

ASK TCE1: "What is the Temperature Difference between the center of the
card and the card edge in degrees centigrade?";

ASK WD1: "What is the Width of the card in meters?";

ASK TJC1: "What is the Junction-to-Case Thermal Resistance in C/Watt?";

ASK TCB1: "What is the Case-to-Mounting Surface Thermal Resistance in
C/Watt?";

ASK QP1: "What is the Heat Output (Watts) for the device with the highest
dissipation?";

ASK MA1: "What is the Air Flow Rate in kg/min?";

ASK NOD1: "How many Devices (IC's or transistors)?";

ASK MAT: "What is the Material of the Thermal Plane?";

CHOICES MAT: ALUMINUM, COPPFR;

```

ASK HT: "What is the Height of the card in meters?";

ASK PT: "What is the Package Type for the device with the highest heat output?";

CHOICES PT: DIP, FLATPACK, CHIP_CARRIER;

ASK TEC: "What Device Technology dominates?";

CHOICES TEC: CMOS, BIPOLAR, DONT_KNOW;

ASK FUNC: "What is the Board's Function?";

CHOICES FUNC: MEMORY, COMPUTER;

ASK TH1: "What is the thickness of Thermal Plane in meters?";

ASK NOP1: "How many Pins are on the device with the highest heat output?";



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